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|  | P. E. Green, Jr.<br>R. V. Wood, Jr. |
| Large Aperture Seismic Array Capabilities |  |
|  | 12 July 1966 |

# Lincoln Laboratory

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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# LARGE APERTURE SEISMIC ARRAY CAPABILITIES

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TECHNICAL REPORT 421

12 JULY 1966

LEXINGTON                                    MASSACHUSETTS

# ABSTRACT

This report presents the results of o study of the effectiveness of the experimentol Lorge Aperture Seismic Arroy in Montono. An ottempt hos been mode, where possible, to drow conclusions from the study of this one stotion obout the performonce thot might be expected from o worldwide net of severol of them.

The report discusses the reliobility ond continuity of observotions obtainoble from o LASA system, the threshold level for outomotic detection ond locotion of weok events, the vorious signol-to-noise enhoncement processes ovoiloble for on-line ond off-line use, ond the effect of such enhoncements on the obility to discriminote source type.

The engineering opprooches ond system organizotion that were chosen oppeor to hove resulted in o system of high reliobility in the presence of normol component foilures, noise, ond seismic interference. The 50-percent detection threshold being currently achieved by relatively crude on-site processing is estimoted ot mognitude 3.5. Off-line processing goins in signol-to-noise rotio equivolent to o magnitude differentiol of 1-1/4 over o single seismometer output ore ovoilable. The improvement in obility to see waveform feotures for identification depends on the type of feature being examined. For first motion, it varies with the signolta-naise gain; for pP, it is significontly lorger.

## CONTENTS

# LARGE APERTURE SEISMIC ARRAY CAPABILITIES

## I.  INTRODUCTION

The Large Aperture Seismic Array (LASA) installed in eastern Montana is intended for advanced research in seismology and nuclear test surveillance.  In particular, it serves as a facility to test the advisability of undertaking an interconnected worldwide network of such stations.  The LASA differs from more classical seismological observing stations in having a large number of seismometers spread over a large area, and in using the latest digital control, signal transmission, recording, and processing techniques.

The experimental LASA has been operating since the late summer of 1965 and has provided a number of quantitative results, some obtained on-site in Montana, and others obtained at Lincoln Laboratory from recorded data.  This report presents these results and attempts to appraise the capability of the LASA class of system in the detection, location, and identification of teleseismic events.

To a great extent, it is virtually impossible to deduce the effectiveness of a global network of LASAs from the results obtained at just one.  This is because completely effective source location and source identification require that the event be received by several stations which have large separations in azimuth.  Therefore, the material in this report will emphasize characteristics of an individual LASA, although the relevance of the various results to a LASA system will be commented on wherever possible.

The structure of the experimental LASA has been described in detail elsewhere,[1] so only a summary of the relevant facts will be repeated here.  As Figs. 1 and 2 show, the sensing subsystem consists of 525 short-period vertical seismometers distributed in 21 clusters or "subarrays," over a 200-km aperture.  To supplement this, a set of three-component long-period seismometers is currently being installed in a vault at the center of each subarray.  The outputs of all these seismometers are locally amplified and sent by buried cable to a subarray electronics module (SEM) which digitizes and multiplexes them into a single-bit stream which is then transmitted to the LASA Data Center (LDC) in Billings by hard wire and microwave circuits employing suitable modulation and demodulation terminal equipment (MODEMs).  At the LDC, there are two small general-purpose digital machines (PDP-7s) and a small special-purpose digital machine (Texas Instruments Multichannel Filter, or MCF) served by a phone-line input system (PLINS) and a timing unit.  Visual monitoring and remote troubleshooting and calibration of the sensing system are provided by use of a maintenance console.  The computers operate in conjunction with digital magnetic tape units.  Permanent visual records are made on 16-mm film by Develocorder units.  Optional telephone-line transmission of a limited amount of data to remote locations is also provided.
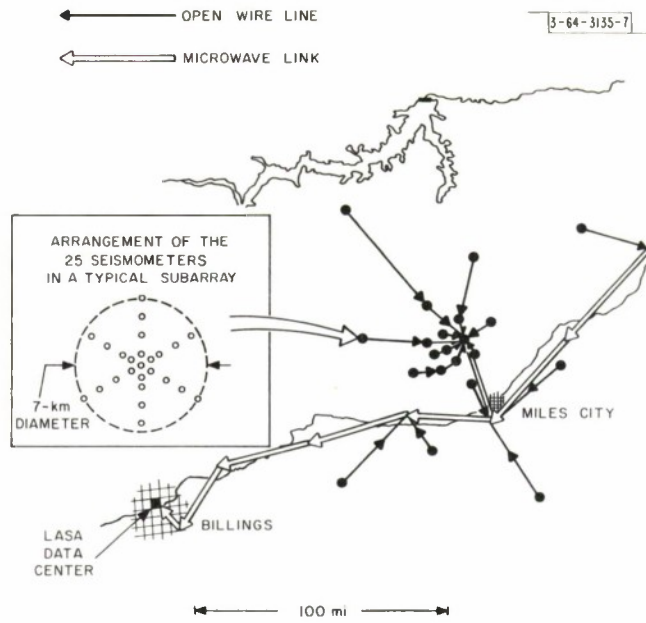
1

3-64-3135-7

ARRANGEMENT OF THE
25 SEISMOMETERS
IN A TYPICAL SUBARRAY

7-km
DIAMETER

MILES CITY

LASA
DATA
CENTER

BILLINGS

100 mi

Fig. 1. Schematic map of experimental LASA.

WIDE-BAND MICROWAVE LINKS

3-64-3798-2

INDIVIDUAL
OPEN-WIRE
CIRCUITS

TAPE UNITS

OUTPUTS

COMPUTERS

PLINS

MODEM

(21)

MODEM

MAINT. CONSOLE

LASA DATA CENTER
BILLINGS, MONTANA

3 L-P
SEISMOMETERS

SUBARRAYS (21)

3
L-P
SEIS.

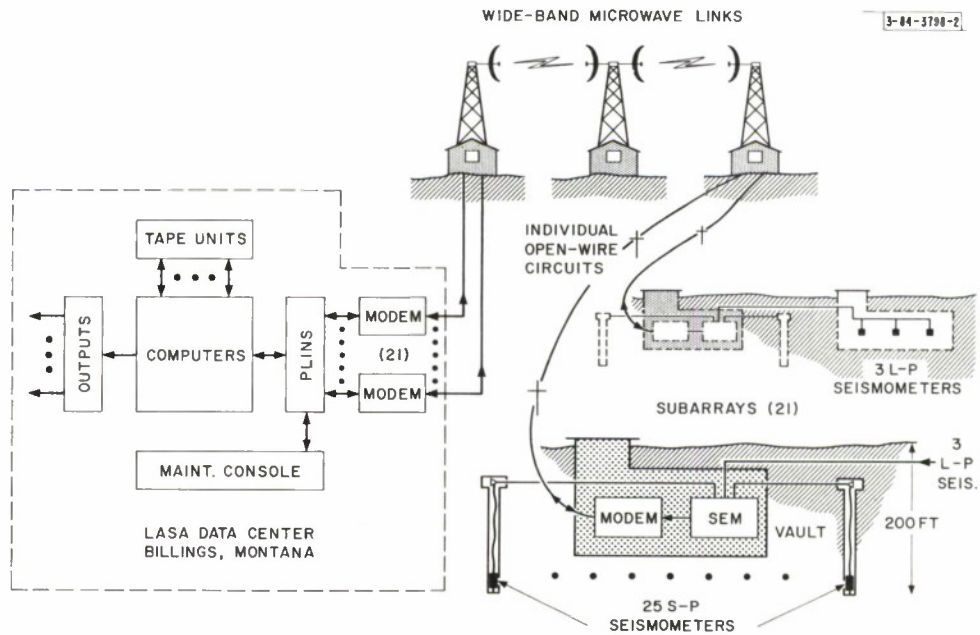MODEM

SEM

VAULT

200 FT

25 S-P
SEISMOMETERS

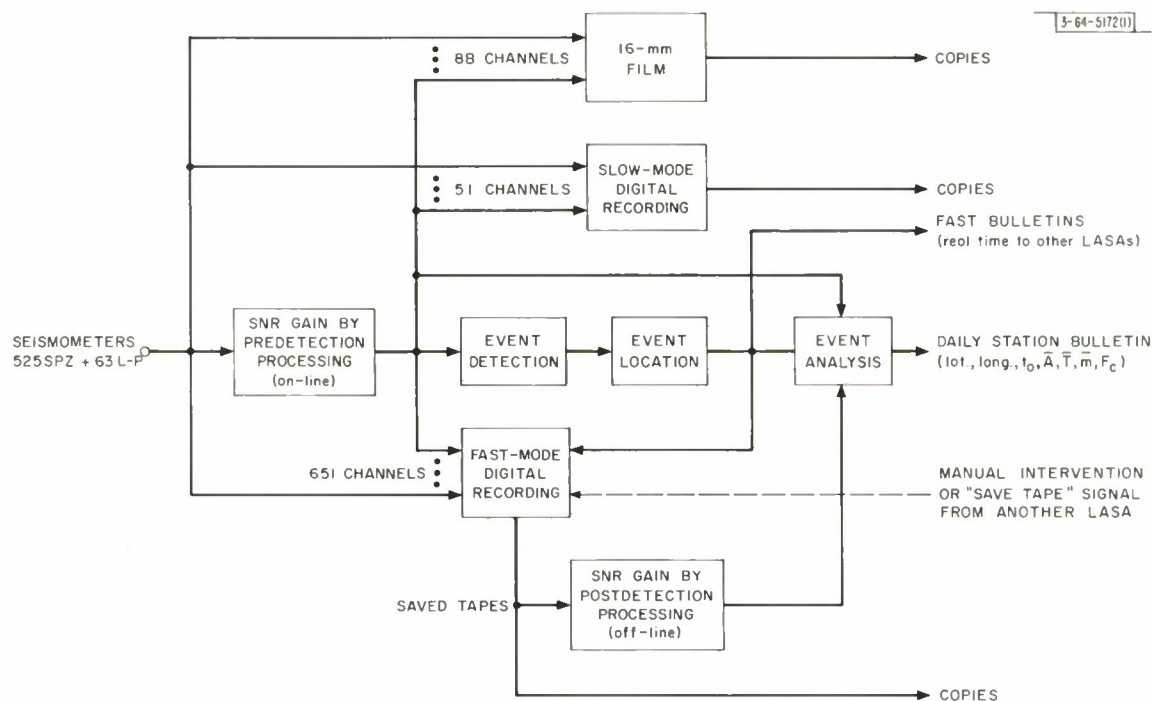Fig. 2. Block diagram of experimental LASA.

2

Fig. 3. Signal flow into and out of LASA Data Center.

The flow of signals through the LASA Data Center is shown in Fig. 3. The reverse flow of commands for troubleshooting and calibrating the system is not shown. At present all the functions in the figure have been automated, except for the event analysis leading to the daily station bulletin; this is being produced manually and is being slowly automated. The predetection processing operation serves the function of increasing the signal-to-noise ratio (SNR) to make the threshold input signal level of automatic event detection and location as low as possible. Two digital magnetic recording options are available: slow mode and fast mode. Slow-mode recordings cover only 51 channels, last 80 minutes per reel and are routinely saved for several months. Fast-mode recordings cover 651 channels and thus last only nine minutes per reel. For economy of magnetic tape, they are therefore saved only upon manual intervention or on a command from other stations or the local automatic event detection and location programs. Thus, the slow mode provides monitoring at partial efficiency all the time and the fast mode provides monitoring at full efficiency part of the time.

The following four sections of this report will attempt to provide answers to the following four questions:

(1) What is the reliability and continuity of the observations that are made with a LASA system?

(2) Down to how small a seismic magnitude can one or more LASAs detect and locate teleseisms? (By "locate" we mean determine crude epicenters for making decisions to save high rate records and for alerting other stations.)

(3) Once teleseisms are detected, located, and recorded, how much improvement in SNR can be obtained by off-line processing?

(4) How much does the available off-line SNR gain increase the effectiveness of blast-earthquake discrimination?

## II. SYSTEM RELIABILITY

A network of stations, each organized as shown in Figs. 2 and 3, has a number of operational advantages and capabilities that are somewhat unusual when the system is compared with seismic surveillance systems of a more conventional type. First of all, the engineering approach has aimed at maximizing reliability and minimizing the number of people required by centralizing and remoting the troubleshooting and maintenance operations, by having so large a number of autonomous subarrays that individual subarray failures are not harmful, and by underground installation of as much of the equipment as possible. Second, the volume of data that must be exchanged among stations is reduced by the automated screening of events by approximate location within each LASA. Thus the interchange of unassociated event time picks between stations is minimal, quite an important factor in any network, and especially so when the station detection threshold is low. Third, the presence of on-site recording and processing capability means that extensive retroactive analysis of events can be made. This tends to reduce the margin between magnitude of events that are just detectable and magnitude at which identification can be made. The look-back capability of each LASA is important to a system of LASAs; our experiments have shown that a fast-mode tape made at one LASA of an event that is undetectable on-line, but is preserved on command from another LASA, will often be quite usable after off-line processing. If a system lacks this look-back capability, there will be a wide margin between detection and identification thresholds.

The factors just enumerated mean that a system of LASAs should operate not only with high sensitivity, but also with high reliability and speed of response. Even though the installation in Montana was intended not as an operational around-the-clock observatory but as a test bed for technique development, nonetheless, some preliminary ideas of system reliability are available and may be of interest.[2] The availability of meaningful data at this time is severely limited by the fact that frequent modifications and tests have been in progress throughout the system.

The sensors have operated very reliably, with only 16 failures of the total of 525 in use in 11 months of operation. A new technique has been developed for calibrating the sensor system across its entire operating band, using a pseudorandom coded test signal whose response is analyzed in the computer.[3] The SEM equipment, MODEMs, and microwave equipment have operated quite reliably. Throughout the system there have been 20 component failures in SEMs in approximately a year. Of the communication facilities provided by the telephone company, there have been no failures that took out all the subarrays. The design goal of less than one error per $10^6$ bits has been surpassed by a considerable margin; it is not clear whether any error control (redundant coding) capability will be required. Only one failure of the PLINS and one of the timing unit have been recorded.

The well-head vault equipment and the digital computers proved to be the weak elements in the system. Early difficulties due to lightning may have been substantially eliminated; statistics from this summer's lightning season will tell. Considerable drift of well-head amplifier gain with temperature has been experienced but is considered controllable by redesign of the units. Only seven outright failures of these amplifiers have been experienced.

The computer main frame and tape units have been subject to random transient failures that require program restart an average of once every 10 hours of operation. Solid failures of the equipment, as distinguished from transient failures, resulted in 30 hours per 360-hour month of unscheduled down time for each PDP-7 machine. Since there are two machines, usually only

the off-line processing has suffered, the on-line coverage being maintained. Tape unit mal-functions have constituted the most serious problem. Persistent efforts to clear up these prob-lems have brought us to the point where we are now willing to ship tape copies from the site to other users without the necessity of trial playouts and waveform plotting. The MCF unit has not been in on-line operation long enough for an evaluation of its reliability.

It is clear that the various problems encountered with the digital computers are not proper-ties of the general approach of using digital machines for field seismic signal processing.

The present limitations on reliability are thus all connected with components and are believed to be either avoidable or are not harmful if the presence of the failures can be accounted for in the processing. No fundamental limitations in the system design due to specific unreliabilities have appeared. Therefore, if a new system were to be designed at this time, there would be only one significant change in the basic engineering design. This is to increase the amount of automated computer surveillance and logging of conditions directly onto the tapes for the var-ious elements of the system. Such a monitor program just for the sensors was used at Billings in the beginning, but as needs for PDP-7 time grew, manual control was reinstituted. Since the constant modification and updating of the system has now tapered off and the system stabilized, it is clear that further experiments on automatic system surveillance techniques are now in order.

## III. DETECTION AND LOCATION THRESHOLDS

The threshold for automatic on-line detection and location of events must be as low as pos-sible, otherwise some events will be missed, although their identification might have been achiev-able with off-line (postdetection) processing (to be described in Sec. IV). The detection threshold is expressed as the seismic magnitude level above which a certain percent of the events actually occurring in some specified source region are detected. A similar threshold exists for the operation of locating a weak teleseism. It is difficult to actually assess these thresholds for the experimental LASA, since one needs another system whose detection and location thresholds are so much lower that one can count the number of events not seen by the LASA and thus deduce the percentage seen.

In this section we describe the results obtained by approaching this problem indirectly. We first assess the detection and location threshold magnitudes when only raw traces are used to feed the computer detection and location operations. These figures lie in a range where comparison with existing stations and networks is possible. We then subtract from these figures the mag-nitude equivalent of the measured SNR gain, relative to a single raw trace, of the predetection processing schemes that combine a number of such traces. This gives us a figure for the thresh-old using the appropriate form of processing. Details of these experiments are given in a re-cent report by Kelly.[4]

Determination of the single sensor detection threshold magnitude can be approached in several ways, but we have found that the most reasonable one is a direct comparison of observed LASA noise and signal levels with those at other sites which have a well-established single sensor magnitude threshold based on several years' observations. The data[5] from the Vela stations at UBSO (Vernal, Utah) and BMSO (Baker, Oregon) were chosen for this purpose. The pertinent comparative data are shown in Table I.

Careful measurements at LASA showed that the usual, irreducible quiet rms noise back-ground in the 0.6- to 2.0-cps P-wave signal region averaged 1.3-m$\mu$ (millimicrons) for the 500-foot "10" sensors which were the ones on which our detection and location programs operated.

| TABLE I | | |
|---|---|---|
| COMPARISON OF LASA, UBSO AND BMSO SINGLE-SENSOR DATA | | |
| | Average Reported Magnitude Relative to CGS | Noise Level (Quiet Conditions) in Signal Band |
| LASA* | +0.2 | 1.3 mμ |
| UBSO | −0.2 | 0.7 mμ[†] |
| BMSO | −0.4 | 0.3 mμ[†] |

\* Level at deep hole sensors. The event detection and location programs operated from these sensors.

[†] Data inferred from Ref. 4.

A number in the range 3 to 6 mμ appears typical for the total rms noise background which is primarily low-frequency microseismic noise. This level is occasionally exceeded by the addition of high-frequency energy from local wind, ranching or roadbuilding activity, or at low frequencies by a rise in the microseism level which occurs a few days of the year. Similar background noise levels at UBSO and BMSO in the signal band are about 0.7 and 0.3 mμ, respectively.[5]

We have measured a rough amplitude, averaged over the LASA array, on digital tapes of 100 teleseisms and compared these amplitudes with those reported to the U. S. Coast and Geodetic Survey (CGS) by the two observatories. The three stations are well within 10 degrees of one another and so the amplitudes were compared directly with no distance corrections. These data are also tabulated in Table I. The scatter is very great and the results depend on the criteria used by the operators, but the data clearly show that LASA signal levels are relatively large. The comparison is probably more meaningful for weak events, where there are fewer cycles of signal to choose from, and hence we compared stations for events recorded at LASA with amplitudes not exceeding 10 mμ. It was found that the amplitudes are on the average higher at LASA by a factor of 2.2 (0.35 magnitude) relative to UBSO and by a factor of 3.5 (0.55 magnitude) relative to BMSO. These two numbers are corroborated by an independent study of a set of 100 events reported to the CGS by all three stations. LASA amplitudes averaged 0.4 ± 0.3 magnitude higher than UBSO amplitudes and 0.6 ± 0.3 magnitude higher than BMSO amplitudes; the 0.3 figures were the standard deviations. A separate comparison of some 300 events places LASA magnitudes higher than CGS magnitudes by 0.2 ± 0.3.

For average signals, a signal-to-rms-noise ratio of about 7 db is required for 75 percent detection on a single trace.[5] This corresponds to a magnitude range at the station of from 4.2 to 4.5 for a distance of 60° and normal depth. The 0.4 magnitude higher level of signals at a LASA 500-foot sensor therefore implies a 75 percent detection threshold for it at a UBSO magnitude of 4.1; that is, a CGS magnitude of 4.3. The corresponding 50-percent detection CGS magnitude threshold is 4.1.

These numbers can be reduced further by subarray delay-and-sum or FS processing, using multichannel filter equipment. These processing options will be defined and described in more detail in Sec. IV. Table II shows results of a number of measurements of SNR gain achieved by a number of on-line predetection processing schemes using the PDP-7 computers and the

multichannel filter (MCF) unit at Billings. Noise suppression and signal loss are listed separately. Signal loss can be caused by improper delay station corrections, loss of waveform coherence across the aperture, and so forth.

Signal-to-noise gains for the existing on-line beams have averaged 12 db or 0.6 magnitude. Off-line repetition of these observations have averaged 0.75 magnitude; most of the difference was caused by the lack of any station corrections in the A, B, C, and D ring subarrays in the present programs at Billings. By subtracting 0.6 from the 4.3 and 4.1 single-sensor figures, we conclude that the threshold magnitude for detection on a single trace being developed by the means now in operation is at a CGS magnitude of 3.5 to 3.7 for 50- to 75-percent detectability. This is for events at the beam center. When more complete station corrections are used, there should be a slight decrease in all these figures. If the events are off the beam center, there is an increase.

Further improvements in the threshold magnitude are clearly possible. As Table II shows, an improvement of 3 db is expected from the addition of station correction data to the interior subarrays, and 1.5 db from steering within each subarray. As will be seen in the next section, the optimum use of the scatter in SNR from different subarrays ("Brennan combining"), instead of equal weighting, provides another 2.5-db gain. These improvements will be made to the present Montana LASA. In any future LASA, increasing the subarray diameter by at least a factor of two should result in a further increase of 5 db. Adding these numbers and subtracting 2 db for typical misalignment of beam and epicenter, we expect the detection threshold of an operational LASA to run about 10 db (0.5 magnitude) lower than current performance in Montana.

The automatic location threshold magnitude can be approached in a way that is similar, but perhaps a bit more direct. Automatic location of events at the LASA Data Center takes place in

two steps. First, a Teleseism Detector Program (TSD), consisting of eight event detectors[6] feeding decision logic, monitors the "10" seismometers (the ones at 500-foot depth) of the E- and F-ring subarrays. If four or more of the detectors trigger within a 20-second interval, this is reported as a teleseism. The individual event detectors are set to operate at a false-alarm rate of one or two an hour, but the TSD false-alarm rate is only two to three per day of continuous operation. The TSD is at least as good as a human observer watching the same eight traces, and probably better. The times of the individual detector reports, plus any new reports in the subsequent 20-second interval are next fed to the second step, the Epicenter Sourcing Program (ESP) which sorts events by rough location as follows. Instead of using the times to find a position directly, we pick a series of test epicenters and test the correlation of the measured pair-wise travel time differences between subarrays reporting with stored theoretical ones (including station corrections) from each test epicenter. The test location with the largest score is printed out. At present, large time picking errors (up to ±0.5 sec) in the individual event detectors limit the location resolution of this scheme to ±15°, but this is being improved.

In one period, roughly four months in duration, 234 teleseisms at distances from 40° to 90° from LASA were reported by the TSD and the times were used to locate 215 of these events; in some cases, manual location was used. In the other 19 cases, CGS location was required. During the same period that the TSD was operating, the CGS reported only 212 events 40° to 90° from LASA, of which 195 (or 92 percent) were among the 234 detected by the TSD. Also during this period there were 70 additional TSD reports, over and above the 234, on which times were too unreadable for epicenter determination. We feel certain that many of the 70 are real events which were not strong enough to be located by CGS.

Figure 4 shows several cumulative number vs magnitude plots of these events. We can use these data to infer a location threshold magnitude, that is, that magnitude above which the TDS detects a given percentage of events well enough for location. Data on amplitude averaged over the LASA on each of the 234 events were converted to earthquake magnitude and plotted in the upper curve as number of events detected larger than a given such LASA magnitude vs that magnitude.
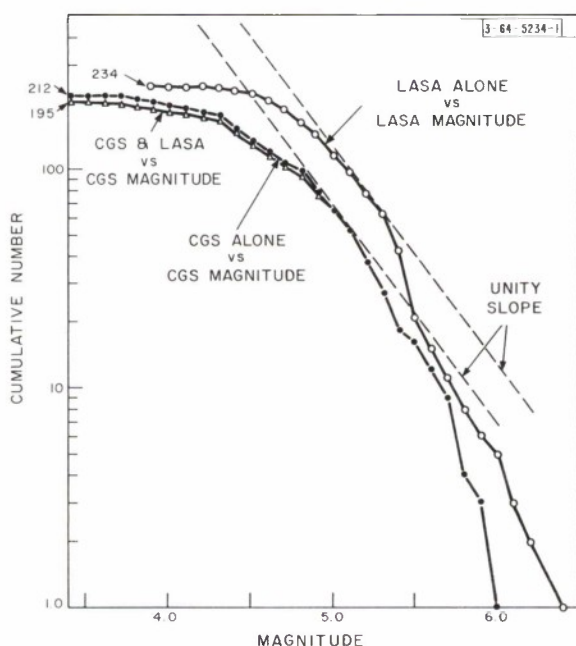


Fig. 4. LASA teleseism detector compared with CGS network.

8

This curve breaks cleanly with a projected hypothetical unity slope seismicity line. The irregular behavior at magnitudes above 5.3 is thought to be caused by statistical instability due to an insufficiently long observation period. If the unity slope line is a correct extrapolation of the seismicity below the break point (and this is the slope commonly observed), then 75 percent of the events above 4.6 are locatable. This corresponds to 4.2 UBSO magnitude or 4.4 CGS magnitude, respectively. Coincidentally, these are not too far from the single sensor detection figures of 4.1 and 4.3 mentioned earlier. Actually, of the 234 detections, 19 were impossible to locate without help from CGS. This adds 0.1 magnitude to the above figures so that we may say that 50 to 75 percent of the events above 4.3 to 4.5 CGS are located.

We turn again to Table 1 to determine the magnitude equivalent to subtract for predetection processing of each of the eight subarrays. Use of the subarray straight sums, which has recently been initiated should lower the threshold by 0.15 magnitude, steered sums in each subarray would produce 0.20 magnitude, and eight MCF units would produce from 0.20 to 0.45 magnitude, depending on the frequency of updating.

## IV. OFF-LINE PROCESSING OPTIONS

All seismic events that are barely detected, and many of them well above the threshold level, require considerable off-line processing before the full resources of a single LASA for identification have been exhausted. As Fig. 3 has indicated, the high rate digital recordings are saved for just this purpose on command from automatic event detection-location programs just described, by manual intervention, or on the basis of dispatches received from other LASAs. The form of processing desired will depend greatly on how visible the signal is before processing, which identifying feature is to be examined, and so forth. The various options available, and their performance in terms of SNR gain, are summarized in this section. Further details are contained in a recent report by Capon, Greenfield, and Lacoss.[7]

In general, two forms of processing options are available, filtering and array processing, that is, isolation of signal from interference on the basis of characteristics in time and space, respectively. We first discuss filtering. The spectral distribution of noise components and the various interesting signal features may concentrate at different frequencies. The solid curve of Fig. 5 shows the spectrum of the noise observed from a typical LASA short-period vertical seismometer. Note the strong microseismic noise component around 1/4 to 1/3 cps. The typical P-wave signal, on the other hand, usually has most of its energy in the 1/2- to 2-cps band, but there are important exceptions to this statement. The first motion usually contains energy up to 3 to 4 cps. Moreover, occasional events may have P-wave center frequencies lying anywhere from 0.7 to 2.5 cps. One frequency region of great potential interest is the 0.1- to 0.6-cps band, which is usually obscured by noise which LASA array processing can very effectively suppress. It is not entirely clear at this time whether any useful discriminants concentrate in this band.

Four increasingly more complicated (but also more effective) forms of array processing are available, as shown in Fig. 6(a-d). They are straight summation of the traces (SS), delay-and-sum (DS), that is, steered or phased sum, weighted delay-and-sum (WDS), and filter-and-sum (FS). In DS the various traces are delayed by appropriate amounts so as to steer the main lobe of directivity at the signal. The beam intensity is proportional to N, the number of sensors, and its width is inversely proportional to the aperture L. In WDS processing, an amplitude weight is applied to each output in addition to the steering delay to point the nulls in the directivity
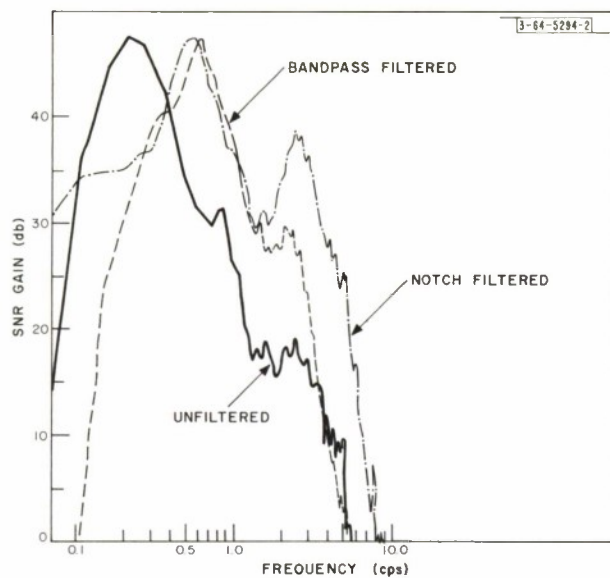
9

Fig. 5. Noise spectra of a typical trace.



(a) Straight sum processing.

(b) Delay-and-sum processing.



(c) Weighted delay-and-sum processing.
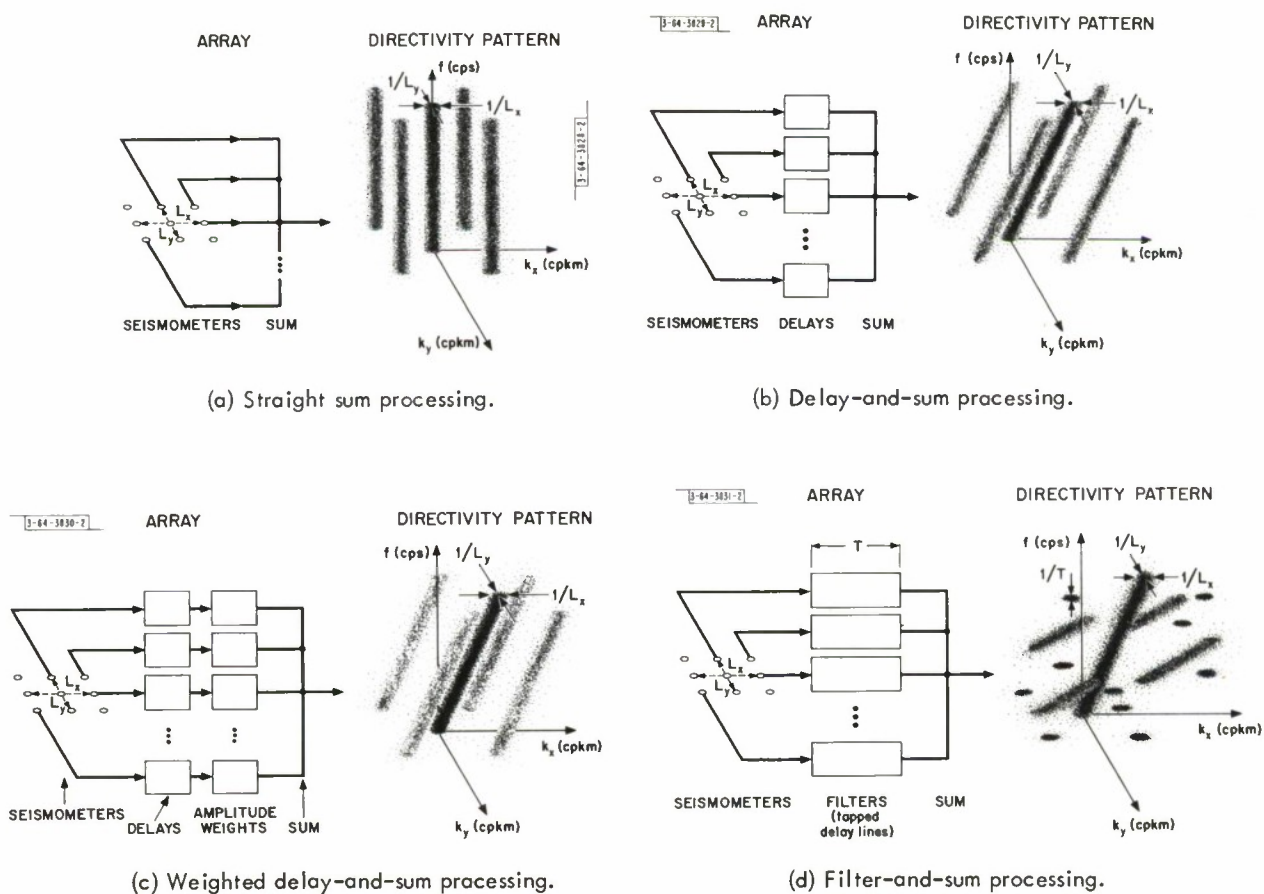
(d) Filter-and-sum processing.

Fig. 6. Block (left) and directivity (right) diagrams for four processing schemes.

pattern at the sources of noise while still pointing the main lobe at the signal. In FS processing, the aiming of the nulls is made frequency dependent by having in effect a different set of N amplitude weights at every resolvably different frequency across the operating frequency band. This can be important in working against seismic noise, since this noise has widely different directional properties at different frequencies. As we have employed it, however, FS processing is of a type (maximum-likelihood processing) that does not introduce any frequency filtering into the output trace. That is, the signal waveform out of the FS processor ideally looks like the input signal in each of the sensor outputs, just as it does for the other three less complex schemes shown in Fig. 6. This is managed in the FS processing by forcing the N filter functions to add up to unity across the operating band (after the steering delays have been accounted for), so that frequency distortion is eliminated.

In applying array processing to recorded array data, the steering delays are determined by the presumed geographical location of the signal, a deterministic quantity. The weights for WDS or filter functions for FS, on the other hand, are most effective when they are synthesized to work against the particular noise field in which the signal is imbedded. These noise statistics change slowly with time. We have developed synthesis procedures for WDS and FS in which the weights and filter functions are synthesized from a sample of the N noise waveforms observed over a measurement period called the fitting interval, which is usually chosen just prior to the signal arrival. In off-line WDS and FS array processing, we feed a fast-mode LASA tape through a computer program that first measures the noise statistics over the fitting interval, then designs the optimum weights and filter functions and finally forms the N seismometer signals into a single output trace. To do FS on a single 25-element subarray requires 10 minutes of IBM 7094 time; WDS takes nine minutes and DS takes six minutes. Tests have shown that a three-minute fitting interval duration is sufficient and that the effectiveness of the processing drops slowly outside this interval. The drop is negligible for up to 15 minutes' separation. The optimum number of coefficients NFP in each of the N filter functions in FS processing has been found to be 15 to 20.

If on the one hand, the noise and the different signal features concentrate in different frequency bands and on the other hand, the DS, WDS, and FS array processing operation all have a flat frequency response against the signal, then obviously some form of frequency filtering should be applied in addition to array processing. This filtering should be helpful in combatting noise so long as it does not distort the interesting signal features too much. One has a choice of doing the frequency filtering either by applying identical filters to all N channels before the array processing program is applied (prefiltering) or to the single output channel afterward (postfiltering). Neither the operations of prefiltering nor postfiltering should be confused with the individually different filtering operations carried out on the separate traces in FS processing.

For DS it makes no difference which is done, prefiltering or postfiltering, but for WDS and FS there is a difference, and prefiltering is much the more efficient procedure. The reason for this is the following. The processing program deploys the N degrees of freedom in the WDS operation (N amplitude coefficients) or the $N \times NFP$ degrees of freedom in the FS operation so as to act most effectively against the noise. This means the noise seen in the traces by the program that measures noise statistics. If postfiltering were used, the processing might have wasted much of its efficiency against noise in spectral regions that were about to be suppressed anyhow in the postfiltering. Prefiltering of the proper type insures that the degrees of freedom are used most efficiently.
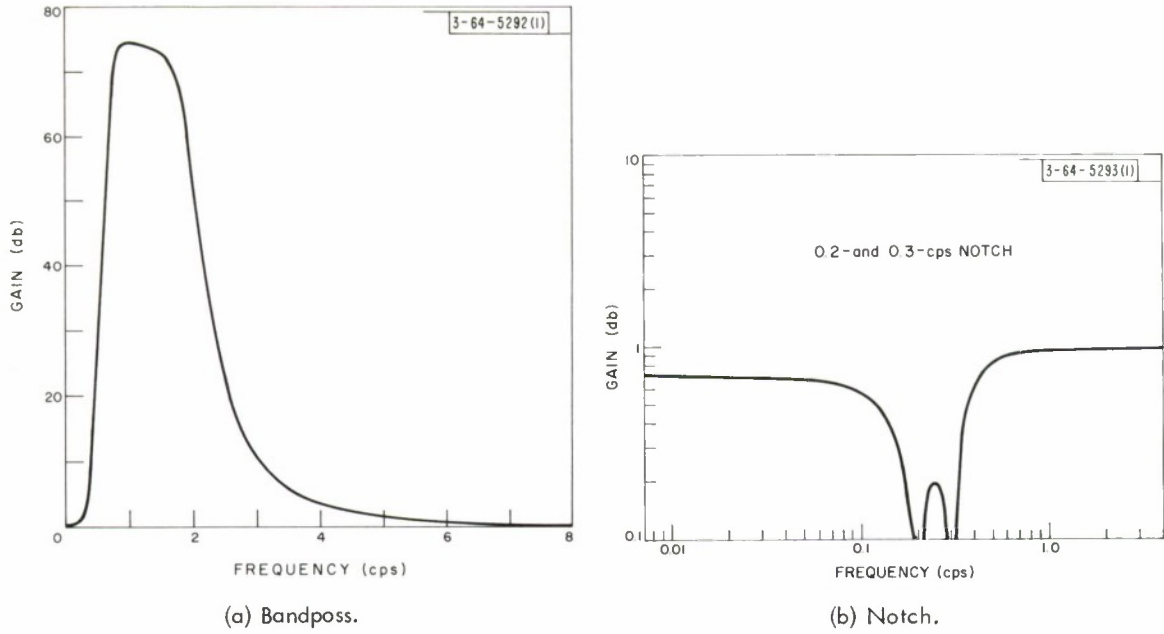
(a) Bandpass.　　　　　　　　　　　　　(b) Notch.

Fig. 7. Frequency response of two types of prefilters.

An unlimited variety of prefiltering conditions is possible. We have found that three handle most of the problems we have encountered with P phases. The first option is to use no pre-filtering. If the problem is simply maximizing P-wave energy, the second option, a 0.6- to 2.0-bandpass prefilter shown in Fig. 7(a), is used. This seriously distorts first motion and artificially extends the coda on extremely simple P phases, although it does not interfere with observation of pP or measurements of complexity on events of average or large complexity. The third option, a notch filter, whose characteristic is shown in Fig. 7(b), is used when first motion observations or accurate complexity measurements are to be made.

The three curves of Fig. 5 show typical noise spectra after each of the three prefiltering options and Fig. 8(a-c) shows typical data for noise suppression obtainable from a typical 7-km 25-element LASA subarray for these three cases. In each figure the behavior of DS, WDS, and FS is detailed as a function of frequency. Noise suppression is defined as the ratio of output power density to power density of a typical input trace (200-foot-deep seismometer), and is expressed in decibels. Twenty decibels in SNR gain is the equivalent of having a signal stronger by 1.0 seismic magnitude unit in the same noise.

Several lines of investigation suggested that a 25-element subarray having diameters larger than 7 km might be more efficient. The geometry of the LASA allowed this to be tested and the results are shown in Fig. 9(a-c) for a 22-km subarray arrangement. A result substantially identical with that of Fig. 9(b) was obtained when bandpass prefiltering was used with a 15-km 25-element subarray. The spectral behavior shown in each of Figs. 8 and 9 is typical of two to three similar runs of noise suppression vs frequency. The detailed curves disagree by as much as 6 db from run to run, but the general trends are the same and the overall noise sup-pression figures agree within 1 to 2 db.

The overall figure is defined as the ratio of total noise level in the output trace to the noise in a typical input trace. Table III summarizes the overall off-line SNR gain achievable for the

12

(o) Na prefilter, 20 November 1965.
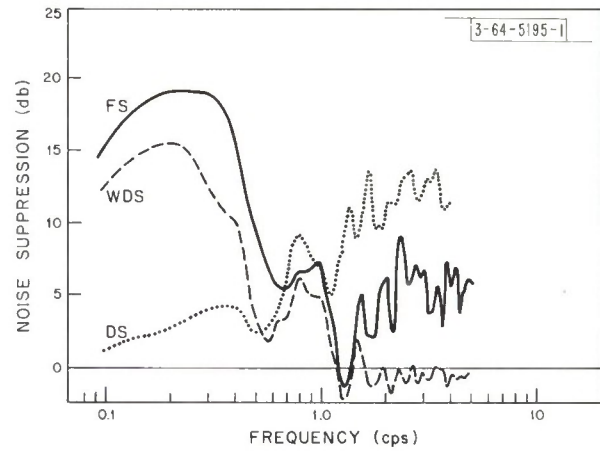
(b) Bondposs prefilter, 11 November 1965.
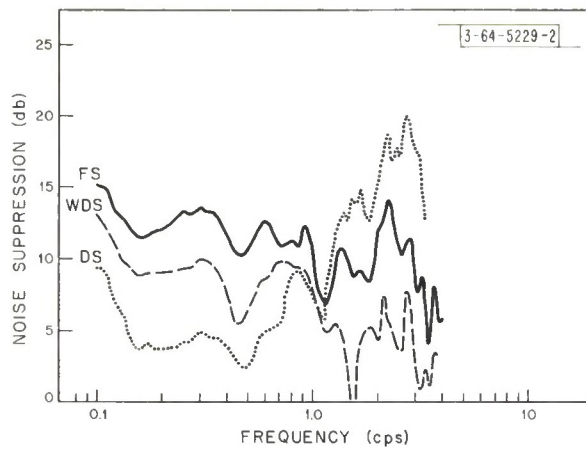
(c) Natch prefilter, 4 February 1966.

Fig. 8.   Noise suppression as a function of frequency for 7-km subarrays and three forms of prefiltering.

(a) No prefilter.

(b) Bandpass prefilter.

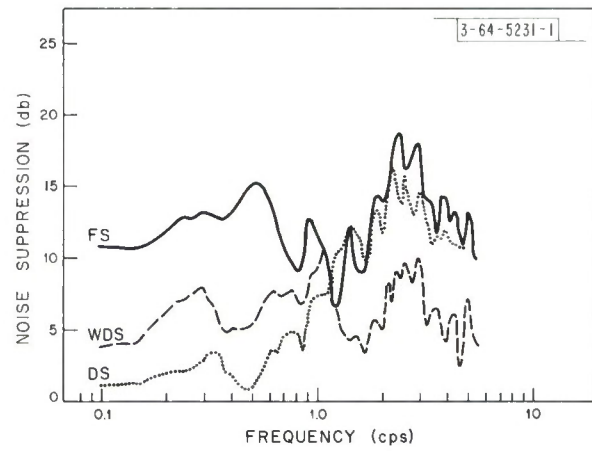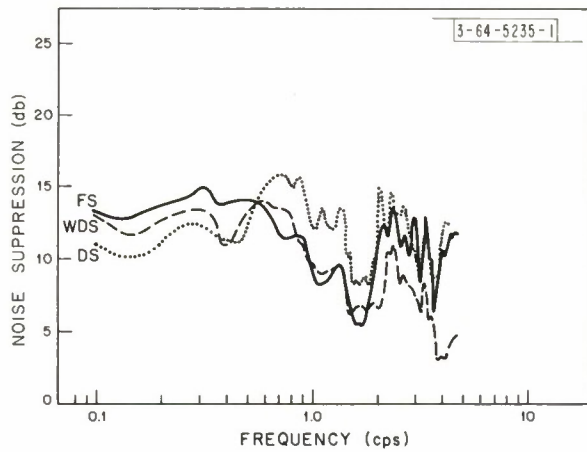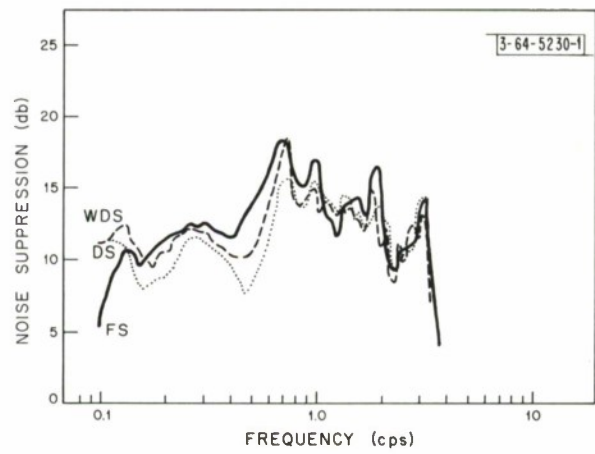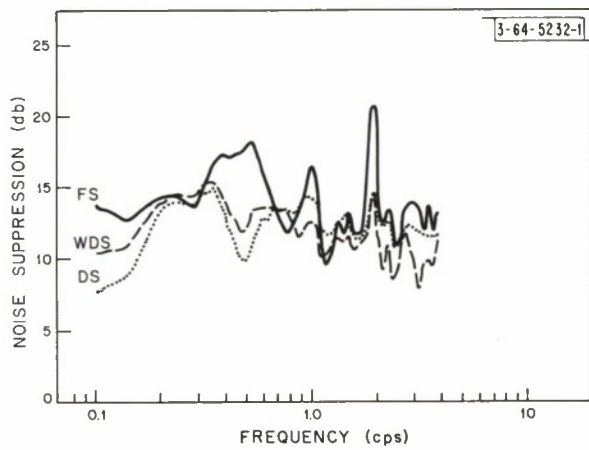(c) High-pass prefilter.

Fig. 9.   Noise suppression as a function of frequency for 22-km subarrays and three forms of prefiltering (4 February 1966).

14

## TABLE III

### SUMMARY OF OFF-LINE PROCESSING RESULTS
(1.0 magnitude = 20 db)

| Form of Prefilter | Noise Suppression 7-km Subarray FS/WDS/DS | Noise Suppression 22-km Subarray FS/WDS/DS | Signal Loss in Subarray FS/WDS/DS | Overall LASA SNR Gain Using 21 7-km Subarrays FS/WDS/DS* | Overall LASA SNR Gain Using 21 15- to 22-km Subarrays FS/WDS/DS* |
|---|---|---|---|---|---|
| None | 18/9/3 | 14/13/11 | 2/1/1 | 31/23/17 | 27/27/25 |
| Bandpass 0.5–2.0 cps | 12†/7/6 | 14/12/11 | 2†/1/1 | 25/21/20‡ | 27/26/25 |
| Notch 0.3–5.0 cps | 12/7/4 | 16/13/12 | 2/1/1 | 25/21/18 | 29/27/26 |

* The three forms of processing listed in these two columns refer to subarray processing. The subarray outputs are assumed combined by DS using amplitude weights, and include the 2 db for Brennan combining.

† Compare the figure quoted in Table II in discussing updated subarray processing using the MCF unit.

‡ This corroborates the 15 db (0.75 magnitude) quoted in Table II far off-line experiments with the Billings beamformer; the difference is that between subarray DS and SS, and inter-subarray Brennan combining.

three prefiltering options (no prefilter, bandpass, and notch prefilter), the three forms of sub-array processing (DS, WDS, and FS), the two subarray diameters (7 km and 15 to 22 km) and one option for combining the 21 subarray signals (DS). Three new factors must be mentioned in explaining Table III. First, the assumption of signal identity across a subarray mentioned earlier is not strictly observed in practice; typical amplitude extremes across a subarray are 2:1. This leads to a loss of output signal amplitude of up to 1 db on DS and WDS traces and 2 db on FS. Second, the amplitudes at different subarrays scatter by even larger amounts, 4:1 or more, so that when subarrays are combined, using a priori information on this scatter to maximize SNR ("Brennan combining"), the result is slightly better than it would be if all subarrays had the same amplitude levels. This gain averages 2 db and is included in the tabulation. Third, over a number of trials combining $M$ subarray traces by DS gave within 1 db of $\sqrt{M}$ additional gain (13 db for $M = 21$). For FS this was just slightly larger, 15 db for $M = 21$. The extra 2 db of SNR gain, however, is ignored in this tabulation for the sake of simplicity.

Although detailed spectral analyses of SNR gain have been made for only two or three runs for each of the six conditions of Figs. 8 and 9, the overall SNR gains for bandpass prefiltering and no prefiltering on 7-km subarrays have been verified by averaging many dozen runs.

Several conclusions may be drawn from the data of Figs. 8 and 9, and Table III. First, the form of prefiltering has a large effect on the available SNR improvement. If no prefiltering is used, the available degrees of freedom go toward SNR improvement in the 1/4- to 1/2-cps micro-seism band, which may be of importance potentially but has not been very useful for P-wave studies.

Second, 15- to 22-km subarrays look very attractive not only for improved SNR performance at higher frequencies, but because almost the whole SNR gain performance can be obtained with the simpler forms of processing (at least at frequencies above 0.6 cps). There will always be some events which will require FS processing, but they should be fewer in number if large sub-arrays are used. (Several examples of look-back processing of weak events are discussed in Ref. 7.)

Third, with the present 7-km subarrays, an SNR improvement of well over one full mag-nitude unit (actually 25 db) is achievable for any of the three prefiltering conditions, and at frequencies below 0.6 cps this is about 1-1/2 magnitude units.

We shall now discuss the implications for identification of this 1 to 1-1/2 magnitude units gain currently available off-line.

## V.  IDENTIFICATION

Most of the criteria applied to teleseismic signal waveforms to identify source type have the property that they must be employed at a number of globally separated sites and the various read-ings combined in order to effect the identification. Thus, hypocenter locations require onset time measurements at a number of stations; first motion observations must be made from a number of stations and suitably plotted in order to use this criterion to characterize an event as unmistakably an earthquake; for depth determination, pP is most reliable if corroborated at several stations (particularly if moveout can be seen); to apply "AR" and other energy ratio criteria, reliable magnitude estimates must be made, an impossibility from a single station; low complexity values must be verified at a variety of azimuths in order to use this criterion to identify explosions, and so forth.

Because of this need for several stations, a definitive appraisal of identification capability of a system of LASAs is by definition unachievable at this time, since the one experimental LASA lies essentially at a single azimuth and distance from each teleseismic source. The problem of determining the identification capability of a network of LASAs by studying the capability of one is even more difficult than the problem discussed in Sec. III of deriving a LASA network detection threshold magnitude from that of one LASA.

So far, no teleseismic identification criterion has been found that is possible at all magnitudes only by use of a LASA, although the search for possible new discriminants goes on continuously. Therefore, as far as we know at this time, the principal advantage inherent in using a LASA is that signals of improved signal-to-noise and signal-to-reverberation ratio are available from it.

Our approach to the problem of rating LASA identification capability has therefore been to observe the increased visibility of important known waveform discriminants using LASA data.[8] In particular, we are interested in the effective decrease in seismic magnitude at which a given seismogram feature can be measured with a certain degree of success. We shall refer to this differential as the "magnitude shift." We have chosen three of the waveform characteristics currently employed for identification, namely, first motion polarity, pP, and complexity, and have compared the visibility of these waveform features on processed traces using the entire LASA relative to visibility on the traces that are available from one subarray. Since one subarray is roughly equivalent in size and number of sensors to an array of the Vela or UKAEA type, this comparison gives us an idea of the gain in performance of a system of LASAs over a system composed of the same number of conventional small arrays.

The form of processing used in our experiment to determine the magnitude shift was delay and sum of the 21 subarray straight sums, a simple scheme that happens to be the one used in the present on-line beamformer. It has a 0.6-magnitude SNR gain relative to one subarray, as can be seen from comparing the first and third lines of Table II, or from Table III.

In an operational situation, a large number of events remain unidentifiable by means of such simple on-line processing and must be passed through further stages of processing. One of the important system characteristics of a LASA is that it has on-site capability for a variety of non-real-time signal processing operations aimed at bringing out the various waveform features of interest. As we mentioned earlier, this look-back capability means that any event for which a high rate tape exists can be subjected to complex off-line processing. Table III shows that in the P-wave signal band (0.6 to 2.0 cps), overall SNR gains of 27 db (1.35 magnitude) are available, that is, 23 db (1.15 magnitude) over subarray straight sums. The effective magnitude shift due to processing can thus be made somewhat larger than the magnitude shift obtained in our experiment that used delayed-sum processing of 21 subarray sums.

In the magnitude shift experiment, an analyst was instructed to read first motion, pP, and complexity for a set of 130 events in two passes. On Pass I, he was allowed to see a chart recording containing a side-by-side display of 15 seismometer traces from a typical subarray (F4) and the straight sum from subarray F4. On Pass II, he was allowed to use a chart recording containing the straight sums from 15 subarrays and the beam formed by delay-and-sum combining of all 21 subarray sums. The set of events was selected from a library of digital tapes of LASA data, and it included all those events for which delays could be picked from 21 subarray sum traces so that the delay-and-sum beam could be formed. The requirement for picking delays from the direct sum traces has resulted in a bias toward strongly recorded events of apparent

| TABLE IV | | | |
|----------|--------------------|----------------------------|--------------------|
| DATA FOR MAGNITUDE SHIFT STUDY | | | |
| Magnitude Range | Number of Events | Amplitude Range (msec) | Number of Events |
| 3.5 – 3.9 | 1 | 1.5 – 3 | 6 |
| 4.0 – 4.4 | 21 | 3 – 6 | 28 |
| 4.5 – 4.9 | 50 | 6 – 12 | 34 |
| 5.0 – 5.4 | 38 | 12 – 24 | 34 |
| 5.5 – 5.9 | 11 | 24 – 48 | 10 |
| 6.0 – | 0 | 48 – 96 | 9 |
| | | 96 – 192 | 6 |
| | | 192 – | 3 |

LASA magnitude 4.0 to 4.5, with a low magnitude cutoff at about LASA magnitude 4.0. The distribution of the set of events in LASA magnitude and amplitude is shown in Table IV.

There is no a priori reason to think that the magnitude shift will correspond exactly to the 12-db SNR differential between the best of the 16 traces visible on Pass II (the beam output) and the best on Pass I (the subarray sum). There is a great deal of collateral information available to the analyst in the other 15 traces on both passes. For example, the amplitude scatter may be such that the subarray used for Pass I is unusually weak or some other subarray is unusually strong on Pass II for some events, or moveout of a signal feature across the array may be recognizable. Thus, phases such as PcP which can often be confused with pP on data from a single conventional station can be properly identified at a single LASA station. As a result, an observation of pP at a LASA station could be more reliable than an observation from a conventional station by a larger margin than can be explained by SNR gain alone. In a sense, the many subarrays of the LASA would be providing the same kind of velocity information only obtainable, when using small arrays, from data from globally separated stations. We shall see that this is actually what occurs.

The results of the experiment for observation of pP are shown in Fig. 10(a-b). Since a large fraction of the events at any magnitude consists of shallow events, the fraction of events of even large magnitudes for which pP is not found is about 40 to 50 percent. The points for Pass I can be seen to break upward significantly above this level around magnitude 5.0. The points for Pass II must also break upward at some low magnitude, but they do not break upward within the magnitude range represented in this set of events. The implication of the lack of an upturn in the observations is that restriction of the population to events for which arrival times can be picked on 21 subarrays has so severely limited the population of small magnitude events that the magnitude shift for pP cannot be determined conclusively from these data; however, a rough lower bound may be inferred.
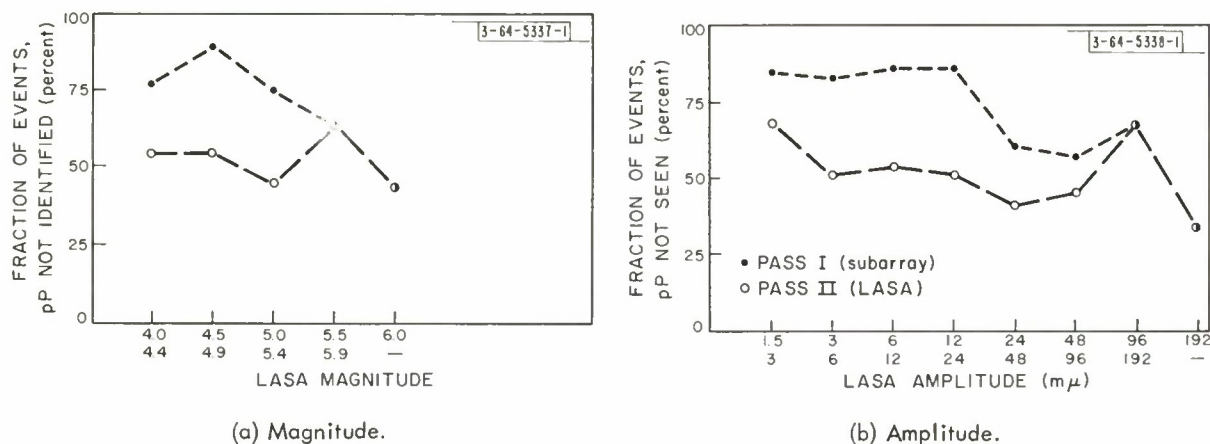
Fig. 10. Inability to identify pP as a function of magnitude and amplitude.

The data are further limited by the possibility that there is no assurance that the base line should stay constant at around 50 percent for the weak events. It is conceivable that a larger portion of weak events is shallow. To test this sort of effect, the failure to observe pP is plotted as a function of amplitude instead of magnitude in Fig. 10(b). Each point on this curve contains data from a range of magnitudes so a baseline shift with magnitude would tend to be averaged out and the curve should indicate a 12-db shift if SNR gain alone is controlling the shift. Here an upward break in the Pass II data is actually visible. The magnitude shift seems to be greater than 20 db, indicating a probable effect from recognition of no moveout relative to P when traces from the full LASA aperture are available. Note that the curve for Pass I in Fig. 10(b) levels off for low magnitudes at about 85-percent failure rate, confirming a false alarm of about 15 percent suggested independently by comparison with CGS depth.

The results of our magnitude shift study for observation of pP between a conventional array (represented by a single LASA subarray) and the LASA thus suggest a shift of about 1.0 magnitude unit, using a processing technique with a signal-to-noise improvement equivalent to only 0.6-magnitude unit.

The lack of data from low magnitude events in our experiment has limited the accuracy of the observation of the magnitude shift for first motion just as much as for pP. The first motion data, summarized in Fig. 11(a-b) suggest a shift on the order of one magnitude unit, but the reduced slope of the curves between magnitude 4.0 and 4.5 indicates a strong bias toward rel- atively large amplitude events at the low magnitudes so that this part of the curve is probably not reliable. Figure 11(b) shows the plot against amplitude, and the amplitude shift of some 15 db suggests that, for first motion, the primary factor affecting the magnitude shift is the SNR gain.

The analyst used coherence of first motion on all traces available to him as a strong factor in acceptance of first motion. In some cases, features with in-band SNR as low as two were used to determine first motion because of their consistent appearance. The fraction of cases for which the determination on Pass I data changed on Pass II is only about 6-1/2 percent, indicating that the criteria were quite strict. A change in the criteria for accepting a determination of first motion should also shift both curves in a similar way so that the indicated magnitude shift would probably not change appreciably if the rules were changed to reduce the false choice rate.

It was difficult to determine a magnitude shift figure for complexity. Many weak events that appeared simple turned out, upon processing, to have fairly complex codas, and conversely
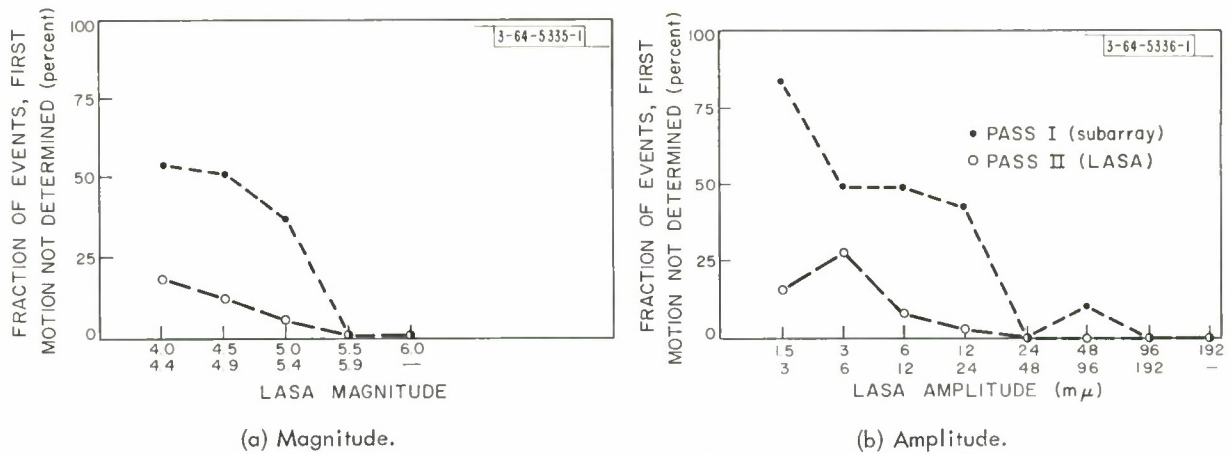
Fig. 11. Inability to identify first motion polarity as a function of magnitude and amplitude.

many that appeared complex because of noise effects turned out to be simple. The effect of the large aperture in producing modest reductions in reverberation was in evidence in a number of cases.

Further details of the magnitude shift experiments on pP, first motion, and complexity (including example seismograms) may be found in the recent report by Briscoe and Sheppard.[8]

One other identification parameter should be mentioned: location. For identification purposes, this implies location using a network, not the rough form of location that is obtainable with just one LASA (about ± 2 degrees rms) and which is useful principally for event screening purposes, as in Fig. 3. Because of the lack of availability of more than one LASA, the problem of accurate multistation location has not been given priority in our studies. One can readily compute from standard formulas the increase of accuracy in picking the onset time of a signal as a function of waveshape and SNR, and certainly the increased SNR available from LASA on stronger events will add somewhat to the accuracy of their location. The real problems are whether the signal will be visible at all and whether travel time biases can be removed. The data on detection threshold given in Sec. III and the data on off-line processing results given in Sec. IV suggest that with each LASA station, reliable observations of onset time down to detection threshold will be possible off-line.

The removal of travel time biases depends partly on the accumulation of data on a number of reasonably strong events from the same region. What constitutes a strong or a weak event may be reinterpreted downward by 1/2 to 1 magnitude unit in considering a LASA network relative to a similar network of small arrays, and 1 to 1-1/2 relative to a single station net.

The possibility of spoofing any of the identification procedures by a determined test ban violator must always be considered. One of the simplest methods and one that is quite effective against networks of single sensors or small arrays is to conduct a test while a large teleseism is in progress. Figure 12 shows the results of a simulation using P from the Long Shot explosion to simulate an interfering teleseism and PcP to simulate the desired one. By using 25 sensors over a 32-km aperture, a suppression of 32 db (1.6 mag.) was obtained on the FS output. This is a fairly severe test since P and PcP are from the same azimuth and separated by only 1.5 beamwidths (of the 32-km array used here).
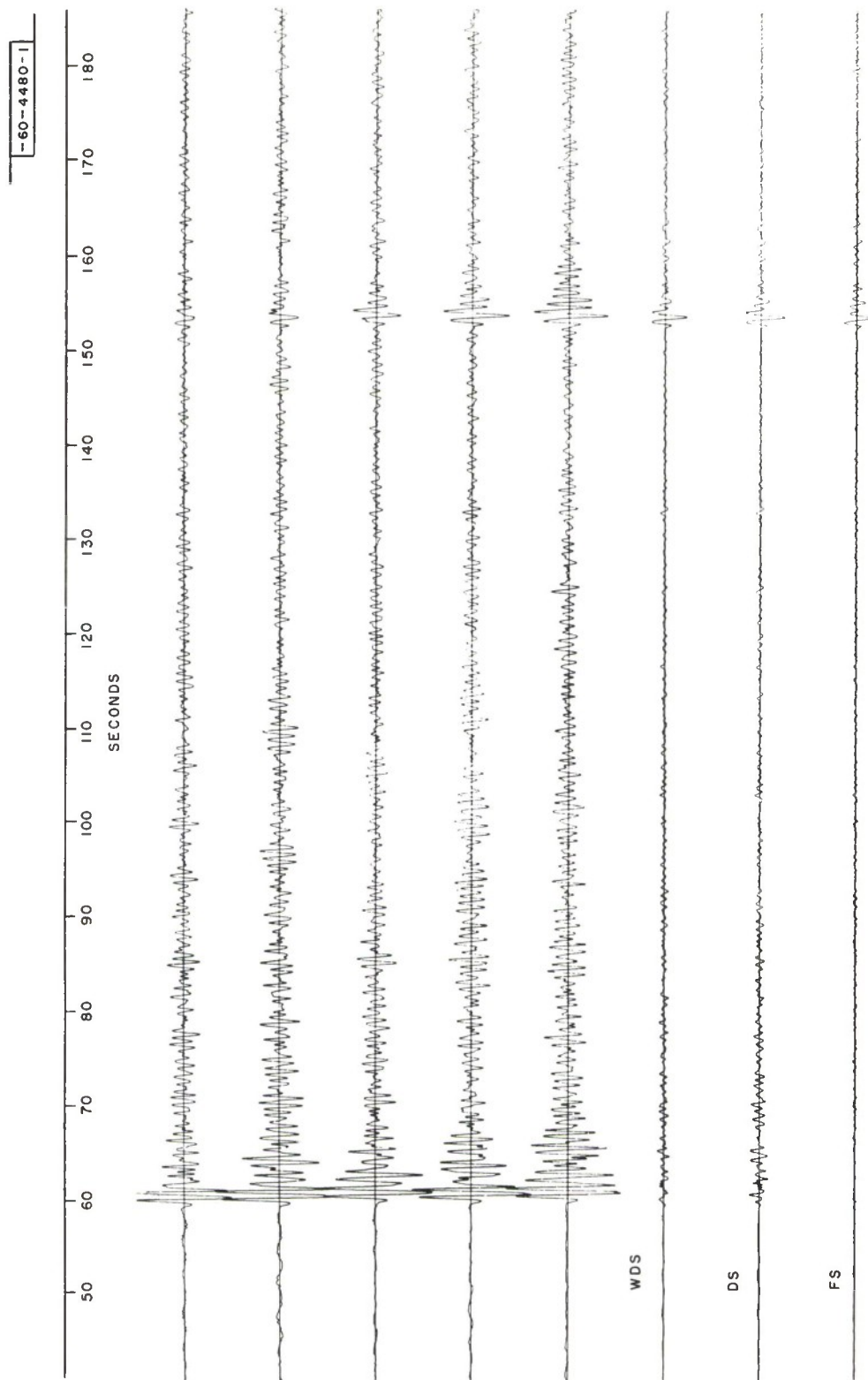
20

Fig. 12. Suppression of one teleseismic signal in favor of another (29 November 1965, Long Shot, 32-km linear array, DS, WDS, FS).

21

## VI. CONCLUSIONS

The results presented in this report suggest several conclusions about the usefulness of arrays of the LASA type for nuclear test surveillance. By such arrays we mean any that include (a) a great enough number (200 to 500) of adequately separated sensors to produce a large signal-to-noise gain, (b) sufficient aperture (roughly 200 km) for rough location, (c) means for automatic detection and approximate location operation, and (d) provisions for making wide-band, large dynamic range recordings for off-line analysis.

1. It is clear that arrays of the LASA type are most useful in the magnitude range in which the noise otherwise interferes with reliable identification using classical stations. For example, LASAs probably are of minimal assistance in the location of an event, or the observation of its first motion, if the waveform onset is already quite clear on single traces, say above magnitude 4-3/4.

2. For purposes of test ban monitoring, however, observations at smaller magnitudes may be required. For a LASA of the type built in Montana, events down to a magnitude of 3-1/2 can be detected and recorded. Off-line analysis can then be carried out on the recorded data to improve SNR by 1 to 1-1/2 magnitude units relative to a typical single seismometer trace, or 3/4 to 1-1/4 magnitude units relative to typical small arrays having no off-line processing capability.

3. The effect of off-line processing on the readability of identification characteristics cannot be inferred from the signal-to-noise gain figures alone. We have found that the diversity inherent in having 21 separately located subarrays introduces additional reliability for certain types of observation, so the effect is somewhat better than that expected from signal-to-noise considerations alone.

4. The ability of a LASA to null out strong interfering teleseisms should provide greatly increased continuity of surveillance during periods of strong teleseismic activity.

Thus, a great many events which are either undetectable or barely detectable in a network of classical stations can not only be detected but also well located and identified with a LASA network. One LASA obviously has negligible capability to perform precise location and identification, but a modest net of two or three such stations should have considerable capability for this.

These are the conclusions for body wave signals; data on surface wave phases will not be available until the long-period seismometers are operating and the data obtained from them are processed.

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**13. ABSTRACT**

This report presents the results of a study of the effectiveness of the experimental Large Aperture Seismic Array in Montana. An attempt has been made, where possible, to draw conclusions from the study of this one station about the performance that might be expected from a worldwide net of several of them.

The report discusses the reliability and continuity of observations obtainable from a LASA system, the threshold level for automatic detection and location of weak events, the various signal-to-noise enhancement processes available for on-line and off-line use, and the effect of such enhancements on the ability to discriminate source type.

The engineering approaches and system organization that were chosen appear to have resulted in a system of high reliability in the presence of normal component failures, noise, and seismic interference. The 50 percent detection threshold being currently achieved by relatively crude on-site processing is estimated at magnitude 3.5. Off-line processing gains in signal-to-noise ratio equivalent to a magnitude differential of 1-1/4 over a single seismometer output are available. The improvement in ability to see waveform features for identification depends on the type of feature being examined. For first motion, it varies with the signal-to-noise gain; for pP, it is significantly larger.

**14. KEY WORDS**

| | |
|---|---|
| LASA<br>seismic array | seismology<br>nuclear test surveillance |